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Use of engineering tools in modelling first bite – case study with grilled pork meat

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Abstract. This study provides an engineering approach in modelling the first bite. Based on the mechanical properties of grilled pork meat obtained by applying compression and Warner Bratzler tests and using the Finite element method, a 3D model of cubic pieces has been created. It was then used for simulating the first bite of pork meat grilled at two temperatures and three positions of the jaws. Stress distribution during impact of upper and lower jaw shows growth of internal stress in the direction of jaw movement, leading to crack development and breaking of meat.

1. Introduction

Meat is a postmortem skeletal muscle tissue of animals [1] and is subject to a variety of physiological and biochemical changes after slaughter [2]. It is a combination of muscle fibres, intramuscular connective tissue and intramuscular fat [3]. The complexity of meat depends on various parameters, such as species/breed, age and muscle position in the carcass [4]. Meat and meat products are complex systems and can be referred to as matrices of interacting components that can be determined by processes and forces operating at the micro-scale [5].

The finite element method (FEM) is an engineering tool, increasingly used in food science. As such, it is capable of analysing and modelling the deformation behaviour of food by solving complex mechanical problems [6]. In meat science, it has been used mainly for analysing mass/heat transfer [7-9], with no studies simulating the first bite. The aim of this research was to measure mechanical properties of grilled pork meat and, based on the results, perform a first-bite modelling simulation using the FEM.

2. Materials and methods

Pork meat (m. *longissimus dorsi*) was purchased locally in Zemun, Serbia, and grilled using two pre-defined grilling regimes (T1 - medium, T2 - long) in a Tefal grill (OptiGrill+). To control the processes, two temperatures were monitored: (i) in meat centres using a digital thermometer (Trotec GmbH - Model BT20, Germany) and (ii) on the surfaces of meat using an infrared thermometer (TES-1327KUSB). To calculate density for both grilling temperatures, 30 samples of grilled meat were cut into cubes of exact measured length, width, and thickness (measured with a digital vernier calliper) as well as mass (measured using an analytical balance (OHAUS Adventurer – Model AR2140, USA) [10].

2.1. Mechanical properties

Mechanical properties of the grilled meat cubes were determined by performing compression and Warner-Bratzler shear tests. All samples had cubic dimensions ($20 \times 20 \times 20$ mm), and both tests were performed in 15 replicates. Grilled pork meat was cubed using thin-bladed sharp knives to minimize damage to the fibres and taking into account their direction [11].

Compression test was conducted on a Brookfield CT3 Texture Analyser using the following settings: test speed - 1 mm/s, trigger load - 10g, target mode - 30%, cylindrical probe - 50.8 mm diameter. Warner-Bratzler shear test was conducted on a TA.XT plus Texture Analyser, under the following parameters: test speed - 1 mm/sec, target mode - distance (21 mm), sample shape - rectangular, selected probe - HDP/WBV, load cell - 50 kg. Both tests were performed on all three planes of each cubic meat sample (Figure 1).
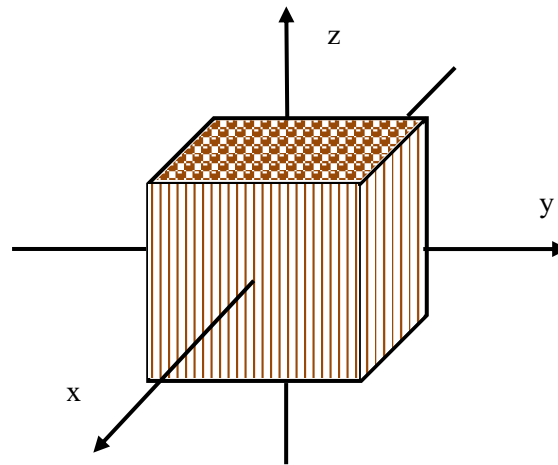

Figure 1. Orthogonal isometric view of a cubic meat sample used for 3D modelling - grilling surface (xOy plane); direction of fibres parallel with the z-axis

Using previous works of Vallespir, Rodríguez, Eim, Rosselló and Simal [12] and Nieto, Vicente, Hodara, Castro and Alzamora [13], true stress and strain were calculated (Equations 1 and 2, respectively). Rupture stress (σ_R) and strain (ε_R) were extracted from the first peak of the stress-strain curve, while Young's modulus (E_d) was calculated for the common linear part of the stress-strain curve, as presented by Djekic, Ilic, Guiné and Tomasevic [14], Equation 3.

$$\sigma_R = \frac{F(t) * (H_o - H(t))}{A_o * H_o} \tag{1}$$

$$\varepsilon_R = ln \frac{H_o}{H_o - \Delta H} \tag{2}$$

$$E_d = \frac{\sigma_R}{\varepsilon_R} \tag{3}$$

Legend: $F(t)$ – force at time t; H_o – initial sample height; ΔH – height difference; $H(t)$ – height at time t; A_o – sample area.

Although meat could be considered as an anisotropic material, for the purpose of this study, the authors assumed the following: (i) grilled meat is an orthotropic material, with three perpendicular planes of material property symmetry (Figure 1); (ii) during compression tests, expansion of meat in the direction perpendicular to the specific loading direction is equal in the other two planes with constant volume before and after loading; (iii) the Poisson's ratio is the ratio between the transversal (lateral) strain and the longitudinal strain ($\nu_{ij} = -\varepsilon_j/\varepsilon_i$), where ν_{ij} corresponds to an expansion in direction "when compression is applied in direction ".

2.2. First bite simulation

Cubic 3D solid models of grilled meat were created using SolidWorks Simulation FEM code. For mesh construction, tetrahedral solid element type was used with 50,406 elements and 71,869 nodes as proposed by Wang and Sun [15], who modelled roasted meat with four-node tetrahedral elements. Our simulation assumed the following: (i) 3D model is a 20×20×20 mm cube (ii) first bite is perpendicular to the longitudinal direction of fibres and parallel to the x-axis; (iii) first bite force was assumed as the value obtained from WB test divided by two, considering the upper and lower jaws.

Simulations were performed for three positions of the first bite calculated as line pressures 20 mm long and assuming tooth width of 1 mm. The positions were in the middle of the biting plane (10 mm from each edge); biting at one third (6.67 mm) from one edge, and at one quarter (5 mm) from one edge, Figure 2.
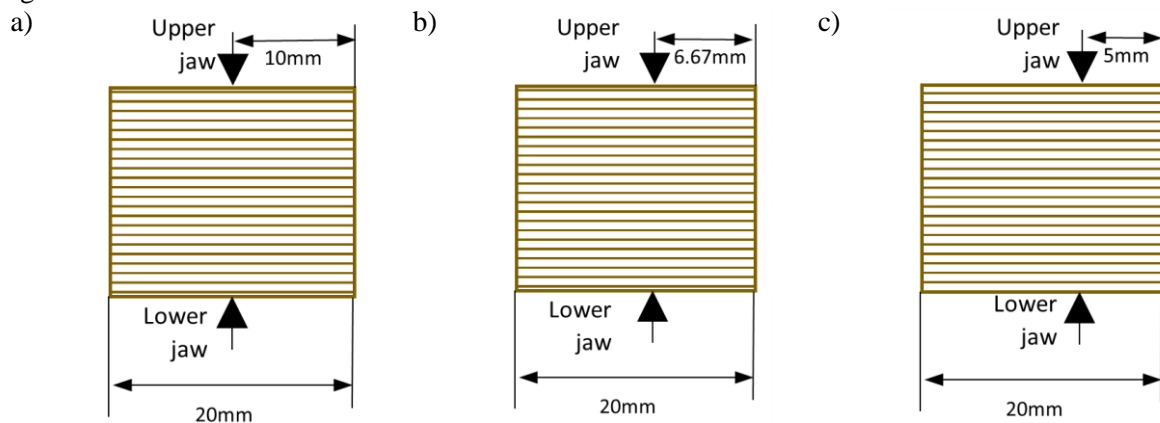

Figure 2. Front view of the positions of upper and lower jaws in the simulated 3D models

3. Results and discussion

From Figure 1, the meat's grilling surface was set on the plane perpendicular to fibres that were parallel to the z-axis. For grilling temperatures T_1 and T_2, values in the centre of the product were 74.6°C and 90.6°C, while on the surface, values were 263.4°C and 272.1°C, respectively. The density of meat grilled at the lower temperature was 1.23 g/cm^3 compared to 1.17 g/cm^3 obtained for the higher grilling temperature.

Firmness values obtained by the Warner-Bratzler Shear Force test show increase with the increase of grilling temperature (64.5 N compared to 79.3 N). This test measures the maximum force needed to cut off a meat sample [16], so the authors used these values as the biting force for first-bite modelling. Rupture stress, ε, was between 0.06 kPa and 0.08 kPa for T_1 and between 0.06 kPa and 0.07 kPa for T_2, calculated for all three directions. Rupture strain, σ, in the three directions ranged between 3.4 and 6.7 for T_1 and 5.4 and 7.3 for T_2.

Values of Young's modulus in the three directions also increased with the increase of grilling temperature, so the obtained values were between 54.3 and 75.3 kPa (T_1) and 111.1 and 148.8 kPa (T_2). Finally, Poisson's ratio was between 0.319 and 0.491. This concurs with some previous studies that reported Poisson's ratio of meat and meat products between 0.2 and 0.49 [17, 18]. As most soft tissues are roughly incompressible (Poisson's ratio up to 0.49), this justifies our assumption that when a material is compressed axially (in one direction), it expands laterally in the other two directions [19, 20].
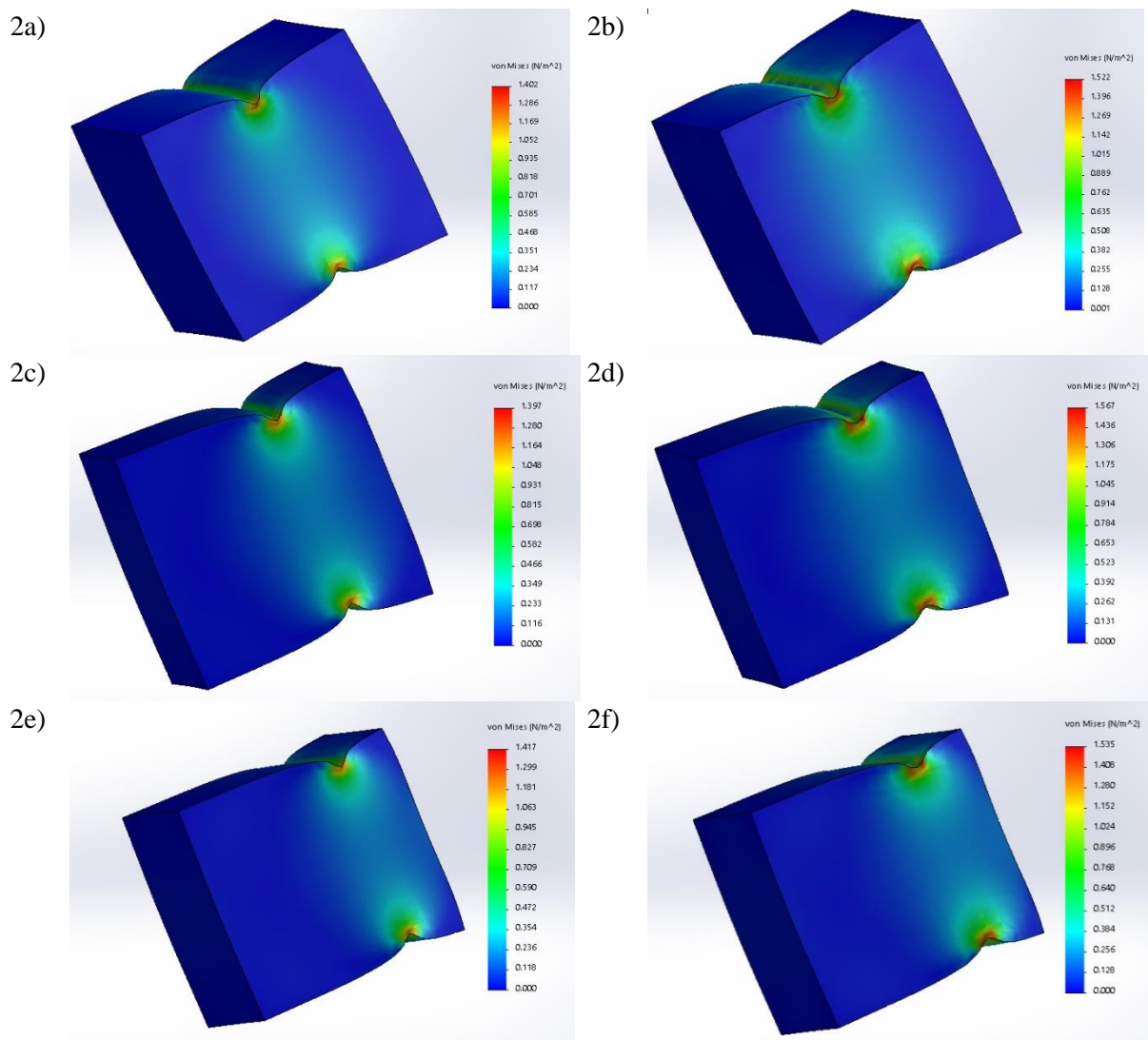
Figure 2. Stress distribution during impact of upper and lower jaw shown for the six models: a) pork meat $T_1 - x/2$; b) pork meat $T_2 - x/2$; c) pork meat $T_1 - x/3$; d) pork meat $T_2 - x/3$; e) pork meat $T_1 - x/4$; f) pork meat $T_2 - x/4$. Colour scale bar indicates gradient areas (from maximum to minimum) of von Mises stress (N/mm^2) in the direction of pressure.

Based on the Warner-Bratzler values, the pressures applied at first bite were 1.61 N/mm^2 for T_1 and 1.98 N/mm^2 for T_2. According to the FEM simulation, higher values for von Mises stress were obtained for the higher grilling temperatures (1.522 N/mm^2 – 1.567 N/mm^2 for T_2 as opposed to 1.397 N/mm^2 – 1.417 N/mm^2 for T_1), showing slight differences regarding the position of the teeth during biting.

Based on the results, this study shows potential in predicting deformations during the first bite [21]. This is notable, since grilled meat has different particle size fragmentation distributions during mastication and before swallowing [22]. The mechanical characteristics of meat directly influence behaviour during oral processing, such as the number of chews, consumption time per bite, chewing cycle, average bite size and/or eating rate [23].

4. Conclusion

This research highlights the potential of using FEM to simulate the first bite of meat and is one of the first of its kind that has tried to connect mechanical properties in modelling the first bite. Results show growth of internal stress in the direction of jaw movement, leading to crack development and breaking of meat. The highest values are in the area of teeth pressure, and as such, lead to the conclusion that upon biting, the meat structure will suffer irreversible damage dividing the grilled meat in two, as happens during the first bite.

Acknowledgement

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